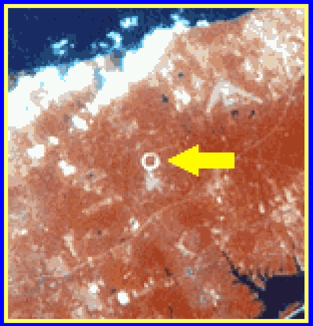
Why RHIC? - the scientific hopes

Gordon Baym

University of Illinois



1982-3

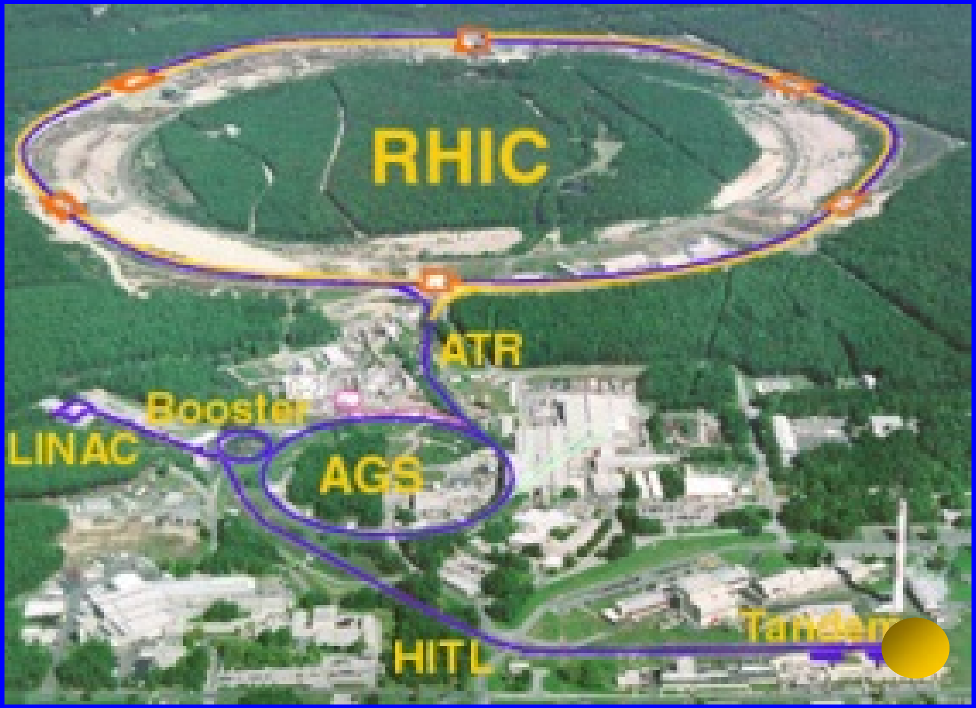
RHIC AGS Users' meeting

May 28, 2008

Why did have in mind when we planned and built RHIC?

What were the scientific motivations?

Have we succeeded in shedding light on the scientific issues?



Thanks to T. Hirano

Pre-history of RHIC

Bear Mountain was the turning point: workshop brought heavv ion physics to forefront as research tool!

“The workshop addressed itself to the intriguing question of the possible existence of a nuclear world quite different from the one we have learned to accept as familiar and stable.”

BNL 50445
(Physics, Nuclear – TID-4500)

Report of the Workshop on

BEV/NUCLEON COLLISIONS OF HEAVY IONS – HOW AND WHY

November 29–December 1, 1974

Bear Mountain, New York

Supported by
NATIONAL SCIENCE FOUNDATION
and
NEVIS LABORATORIES, COLUMBIA UNIVERSITY

Organizing Committee
A. KERMAN, L. LEDERMAN, T.D. LEE, M. RUDERMAN, J. WENESER

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Stability and variability of the vacuum

Is the vacuum a medium whose properties we can change?

``We should investigate … phenomena by distributing high energy or high nucleon density over a relatively large volume." T.D. Lee

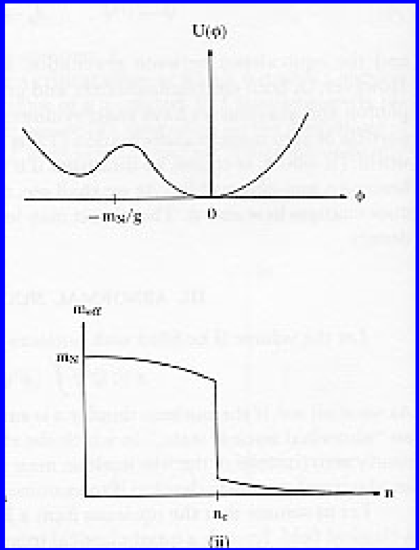
Possibly restore broken symmetries, create dense abnormal states of nuclear matter at high ρ by heavy ions collisions:

Lee-Wick low mass nucleon matter?

pion condensates?

stable abnormal nuclei?

detectable in high energy cosmic rays?



"I name this place Terra Incognita."

Were we playing with fire?

Could seeds of unusual states set off a global catastrophe?

"Lee-Wick theory indicates that 10^8 or 10^9 [abnormal superdense nuclei] have already been produced on the moon, and that the moonis still there, albeit with large holes."   Leon Lederman

The New York Times
nytimes.com

March 29, 2008

Asking a Judge to Save the World, and Maybe a Whole Lot More

By DENNIS OVERBYE

The New York Times
nytimes.com

September 11, 2001

Physicists Strive to Build A Black Hole

By GEORGE JOHNSON

April 15, 2008
Essay

Gauging a Collider's Odds of Creating a Black Hole

By DENNIS OVERBYE

What are the properties of matter under extreme conditions? High temperature, high densities!

Bear Mountain 1974:

Lee-Wick abnormal matter
Hagedorn hadronic resonance gas
Walecka mean field model

Quark matter ("quark soup") as ultimate state:

Itoh 1970, Carruthers 1973

Gross, Wilczek & Politzer, Asymptotic freedom of QCD, 1973

Collins and Perry, 1975: Ultra high density and ultrahigh temperature ⇔ asymptotic freedom. "Bjorken scaling implies that the quarks interact weakly."

Quark matter in neutron star: "Can a neutron star be a giant MIT bag?" -- GB and Chin, 1976

Other significant meetings

First workshop on ultra-relativistic nuclear collisions, Berkeley, May 1979.

High-energy nuclear interactions and the properties of dense nuclear matter, Hakone, July 1980.

Statistical mechanics of quarks and hadrons, Bielefeld, Aug. 1980

Workshop on future relativistic heavy ion experiments, GSI, Oct. 1980

Quark matter formation and heavy ion collisions, Bielefeld, May 1982

How to get going??

June 28, 1983 memo from David Berley (elementary particle physics, NSF) to Harvey Willard, (nuclear physics, NSF), despairing of the possibilities of future heavy-ion experiments, except possibly at ISR (CERN)

MEMORANDUM

DATE: June 28, 1983

To : Dr. Harvey B. Willard, Head, Nuclear Science Section

From : Program Director for Elementary Particle Physics

Subject: Heavy Ion Collisions at High Energy

I have had several discussions with Dr. Ralph D. Amado, University of Pennsylvania and Dr. Gordon A. Baym, University of Illinois-Urbana about experiments with heavy ion collisions and their role in understanding quantum chromodynamics (QCD). Many of us see few possibilities for heavy ion collisions with sufficient energy to be relevant. The Colliding Beam Accelerator (CBA) at Brookhaven would be a fine facility for such experiments but at this moment, and perhaps some time in the future, its ultimate approval or rejection is uncertain. The scattering of oxygen nuclei from fixed targets is proposed at the CERN SPS; a comparison of p-p and α-α interactions is in progress with a series of experiments at the ISR. The energy available in the SPS experiments may be too low, the nuclear volume available in the ISR experiments may be too small. Unfortunately, the ISR is scheduled to be turned off in mid 1984 before heavier ions will be stored.

If the CBA is not built, we may have no opportunity for decades to observe high energy ion collisions. The opportunity to study the thermodynamics of QCD would be lost to a whole generation of physicists.

To avert this grave loss to science, I suggested to Ralph, Gordon and others that we begin working on the prerequisites that could lead to an international initiative by the U.S. to continue operation of the ISR. Sir John Adams, former Director for CERN II, told me the estimated cost to continue operating the ISR is about $15 million per year. There are additional costs to provide heavy ion capability but I don't know what they are beyond those required for planned acceleration of heavy ions in the SPS. The high energy physics community and the nuclear physics community would have to stand firmly behind such a proposal. Support of HEPAP and NSAC would essential.

I write this note to you to urge you to discuss this matter at the NSAC long range planning meeting to be held in July.

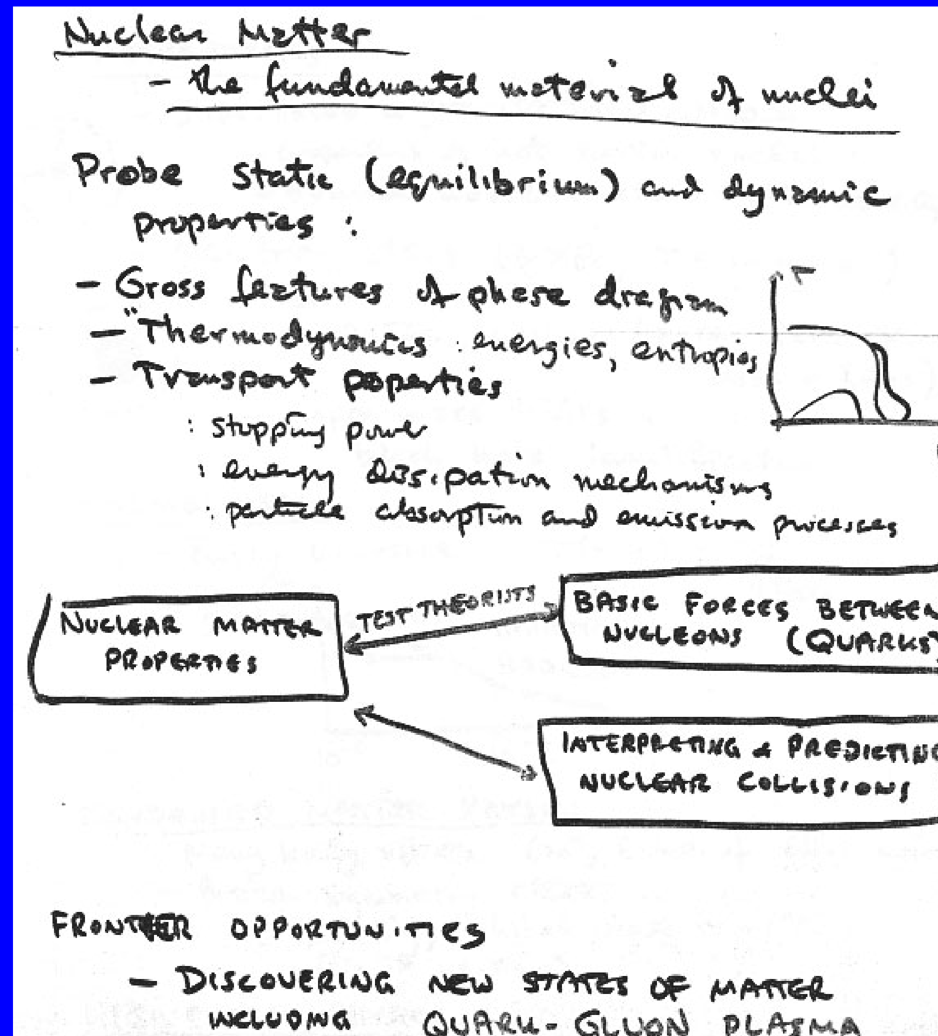
David Berley

cc: Dr. Marcel Bardon, DD/PHY
Dr. Ralph D. Amado, University of Pennsylvania
Dr. Gordon A. Baym, University of Illinois-Urbana

First glimmer of RHIC

NSAC Meeting at Wells College, Aurora, N.Y. July 11-15, 1983

Subgroup on nuclear matter under extreme conditions: *Arthur Kerman, Arthur Schwarzschild, & GB (chair) (NSAC); Miklos Gyulassy, Tom Ludlam, Larry McLerran, Lee Schroeder, Steve Vigdor, & Steve Koonin*



Nuclear Matter

– the fundamental material of nuclei

Probe static (equilibrium) and dynamic properties :

- Gross features of phase diagram
- "Thermodynamics : energies, entropies
- Transport properties
  - : stopping power
  - : energy dissipation mechanisms
  - : particle absorption and emission processes

NUCLEAR MATTER PROPERTIES

TEST THEORISTS

BASIC FORCES BETWEEN NUCLEONS (QUARKS)

INTERPRETING & PREDICTING NUCLEAR COLLISIONS

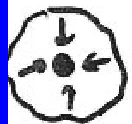
FRONTIER OPPORTUNITIES

– DISCOVERING NEW STATES OF MATTER INCLUDING QUARK-GLUON PLASMA

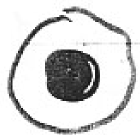
OUTSIDE NUCLEAR PHYSICS

ASTROPHYSICS

- Supernovae a gravitational collapse



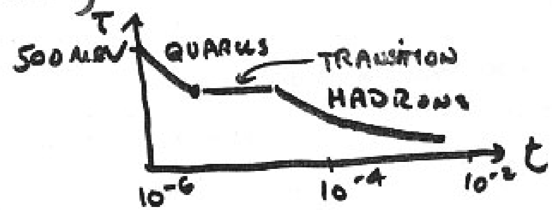
  - properties of hot n-rich nuclei
  - bounce above nuclear matter density ρ_0
- Neutron stars ($\rho > \rho_0$, $T \lesssim 1-10$ MeV)



  - birth
  - evolution, cooling (x-ray satellite observations)
  - upper mass limits & black hole identification

COSMOLOGY

- Early universe $T(\text{MeV}) \simeq \frac{0.5}{\sqrt{t_{sec}}}$



CONDENSED MATTER PHYSICS

- Many body effects (m^*, E dep. of self-energies)
- Broken symmetry states
  : pairing, chiral phase transitions, ...
  ($^1S_0$, $^3P_2$: n-stars)

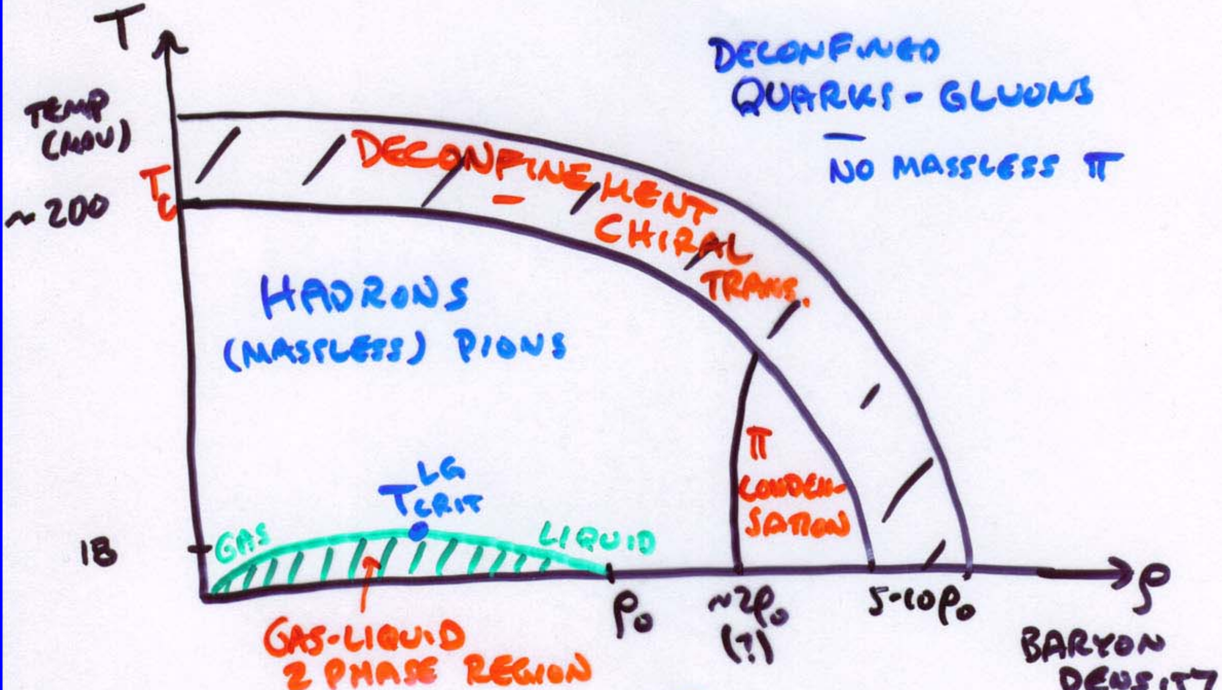
HIGH ENERGY PHYSICS

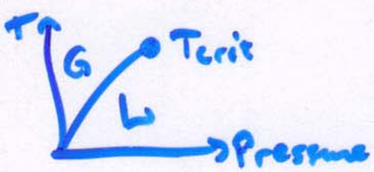
- QCD on large scales

⋮

EXPECTED PHASE DIAGRAM

⇒ MANY OPPORTUNITIES





PLUS
- Z/A DEPENDENCE
- HIGH ANGULAR MOMENTUM DEPENDENCE
- PAIRING ($^1S_0$, $^3P_2$) TRANSITIONS ($T_c \sim 5$ MeV)

Possibility of deconfinement phase transition

Phase transitions

Confinement-Deconfinement

Hadrons dissolve into plasma of quarks + gluons.

Chiral symmetry restoration

$T=0$ $\quad m_\pi \simeq 0$, $m_N \sim 1\,\mathrm{GeV}$

but chiral symmetry $\Rightarrow$

$m_\pi \neq 0$, $m_N \simeq 0$.

Best estimates* from the lattic

* Lattice is small

Light mass fermions somewhat mutilated

but much easier than hadron spectroscopy, or "fine structure" such as nuclei.

Confinement

1st order transition (or non-existant?)

$T_{conf} \sim 140-210\,\mathrm{MeV}$

$\varepsilon_{conf} \sim .5-2\,\mathrm{GeV/fm^3}$

Ideal gas at high T

L. McLerran

Production of exotic objects in high energy nucleus-nucleus collisions

Table 4-3. Partial list of exotica.

Lifetime	Exotic Particles	Primary Signature	Other Signatures
Stable	Complex antinuclei	Normal but negative q/A	Annihilation with $2m_0c^2$ released in calorimeter
	Diquarks[a]	$q = \frac{4}{3}e,\ \frac{1}{3}e,\ -\frac{2}{3}e$	Unusual q/A; $m < 1$ GeV
	Quark-nucleon complexes[b]	Large, nonintegral q	Unusual q/A; frequent $\Delta Z = \pm 1$; favors target fragmentation
	Gluon-nucleon complexes[b]	Unusual q/A	Frequent $\Delta Z = \pm 1$; Z = integer; favors target fragmentation
Metastable	Quark globs[c]	Equilibrium $q/A \approx 0.01$	Strangeness $\approx -A$; $A \gtrsim 10$?; fragments to strange particles
	Chirons[d]	$\langle p_\perp \rangle \approx 10$ GeV/c	Fragments to hadrons with $\lambda_{int} \approx \frac{1}{3}\lambda_{protons}$; large $\Sigma n_h/\Sigma n_\gamma$
	Density isomers[e,f]	Unusual q/A	Nonnuclear A; high p_F; high-E γ decay
$\sim 10^{-4}$ s	Hyperstrange drops[g]	$q/A \approx 0.4$	Strangeness $\approx -1.8A$
$\sim 10^{-10}$ s ?	Anomalons[h,i]	Short λ_{int}	Strong E dependence; frequent ΔZ; high-E γ decay?
	Toroidal nuclei[j,k]	Short λ_{int}	Topological quantum number; γ decay
	"Pi-neut" nuclei[l]	Neutral decay	?
?	Hypostrange nuclei[k]	Decay to fragment and associated strangeness	?

[a]Slansky, R., T. Goldman, and Gordon L. Shaw, "Observable Fractional Electric Charge in Broken Quantum Chromodynamics," *Phys. Rev. Lett.* **47**, 887–891 (1981).

[b]De Rujula, A., R. C. Giles, and R. L. Jaffe, "Unconfined Quarks and Gluons," *Phys. Rev.* **D17**, 285–301 (1978).

[c]Bjorken, J. D., and L. D. McLerran, "Explosive Quark Matter and the 'Centauro' Event," *Phys. Rev.* **D20**, 2353–2360 (1979).

[d]Lattes, C. M. G., Y. Fujimoto, and S. Hasegawa, "Hadronic Interactions of High Energy Cosmic-Ray Observed by Emulsion Chambers," *Phys. Reports* **65**, 151–229 (1980).

[e]Lee, T. D., and G. C. Wick, "Vacuum Stability and Vacuum Excitation in a Spin-0 Field Theory," *Phys. Rev.* **D9**, 2291–2316 (1974).

[f]Boguta, J., "Baryonic Degrees of Freedom Leading to Density Isomers," *Phys. Lett.* **109B**, 251–254 (1982).

[g]Chin, S. A., and A. K. Kerman, "Possible Long-Lived Hyperstrange Multiquark Droplets," *Phys. Rev. Lett.* **43**, 1292–1295 (1979).

[h]Judek, B., "Anomalous Interactions of Secondary Particles Emitted from Relativistic Heavy Primary Interactions," *Can. J. Phys.* **46**, 343–358 (1968).

[i]Friedlander, E. M., R. W. Gimpel, H. H. Heckman, and Y. J. Karant, "Evidence for Anomalous Nuclei among Relativistic Projectile Fragments from Heavy-Ion Collisions at 2 GeV/Nucleon," *Phys. Rev. Lett.* **45**, 1084–1087 (1980).

[j]Chapline, G. F., "On the Possibility of Toroidal Nuclear Isomers," abstract in *5th High Energy Heavy Ion Study*, held at Lawrence Berkeley Laboratory, 18-22 May 1981, LBL-12652 (Lawrence Berkeley Laboratory, Berkeley, California, October 1981).

[k]Goldhaber, A. S., private communication.

[l]McHarris, W. C., and J. O. Rasmussen, "Anomalons as Pi-neuts Bound to Nuclear Fragments: A Possible Explanation," LBL-14075 (Lawrence Berkeley Laboratory, Berkeley, California, March 1982); submitted to *Phys. Lett.*

Emerging knowledge of hadron-nucleus collisions; hints of new physics in nucleus-nucleus collisions

Hadron-Nucleus Collisions

A-dependence of Fragmentation

⇒ Longitudinal Growth Picture of the Hadronization of Partons

⇒ Present Info. on Energy deposition in Nucleus-Nucleus Collisions (Stopping Power)

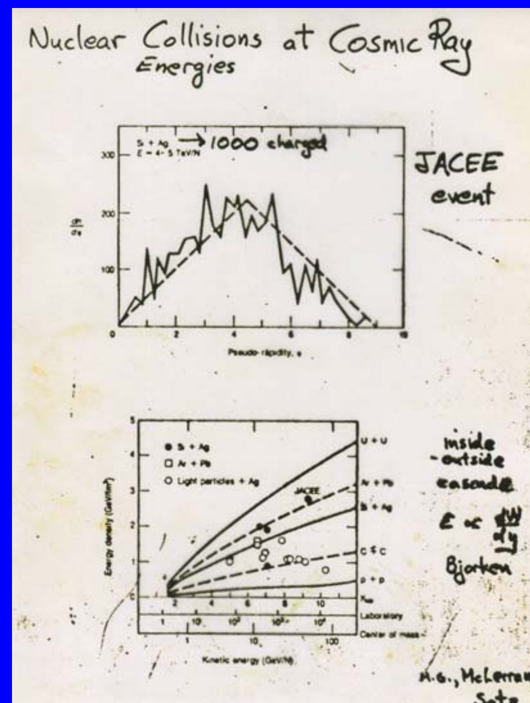
But - Inclusive Expements. No detailed Comparison with dynamical Models.

Surprises in Rare Events:

- Cronin Expt.: $\frac{d\sigma}{dp\,d\Omega} \sim A^{\alpha}$, $\alpha >> 1$ at large P_T
- Fermilab E557 Result: very large Nuclear Enhancement at High E_T

New Phenomena or Tails of Known Processes?

Needed: More complete Measurements



Cosmic ray zoology

Brazil-Japan Emulsion Chamber + Pamirs

Centauros + Chirons

Quark globs? (Isomers, long lived)

Lots of experiments (e.g. Concorde jet event, Texas lone star) Large scale density fluctuations ($\frac{dN}{dy}$); azimuthal symmetry, high $p_\perp$ Quark-gluon fusion burning or detonation?

ADDITIONAL PHYSICS POTENTIAL WITH NUCLEAR BEAMS

1) Equation of State of Nuclear Matter
- continue and extend studies of nuclear matter under extreme conditions
- high T, ρ nuclear matter
- exciting nucleon degrees of freedom (highly excited nuclear matter--N* and Δ-nuclei)

2) Exotica (production of new or unusual states)
- quark-related effects
- metastable phases of nuclear matter
- anomalons

3) Strange-Particle Production
- thresholds:

K^+, Λ^0	1.6 GeV
K^-	2.5 GeV
$\overline{\Lambda}^0$	7.1 GeV

- K^+K^+ interferometry (expect ~ 15 K's at 10 GeV/N for central U-U collision)
- measure source size, expect $R_{K^+K^+}$ ~ min at ρ_{max}
- $\Lambda^0, \overline{\Lambda}^0$
- hyper and multi-hyper nuclei (NN → $KN\Lambda^0$ + coalescence)

4) Pion Production
- most abundant of the hadrons
- source of pions: (Δ, N*) + mesons (η, ρ, ω, f,...), also hadronization of ($q\overline{q}$) pairs associated with plasma
- available energy into pions or compression?

5) Fragmentation Processes
- electro-magnetic dissociation enhanced at high energies
- nuclei far from stability, secondary beams for study
- applications to cosmic ray work ($\sigma_{fragment}$) and instrument calibration

6) Low Energy Program (below threshold)
- emphasis on heavy projectiles (A > 150) not available at other facilities
- liquid → gas phase
- nuclear hydrodynamics

7) Atomic Physics
- QED effects in few-electron very-heavy ions, including one-electron uranium (e.g., Lamb Shift)
- many-body QED effects become significant
- relativistic corrections to fine structure levels > non-relativistic contributions

RESOURCES + NEEDED FACILITIES

1) Present heavy ion machines ($E \lesssim 2$ GeV/A LAB)
   - Providing extensive inf. on collective behavior, dynamic correlations, ...
   - ε ($\lesssim 0.7$ GeV/fm^3), ρ ($\lesssim 3$-$4\rho_0$) well below what can be attained
   - Well below quark-gluon plasma
   - Recommend continued support.

2) Fixed target proposals : 10-15 GeV/A for $\lesssim$U.
   - Maximize nuclear compression : $\rho \sim 5$-$10\rho_0$, $\varepsilon \sim 1.3$-3 GeV/fm^3
   - High priority

3) Other options
   i) Ions in SPS as trial expts
      - ^{16}O in Jan-Feb. 1986
      - Ca upgrade (international cooperation)
   ii) Renting the ISR after last α-α, d-α runs.

4)

Substantial theoretical work
- nuclear fragmentation regions
- Central rapidity regime (early univ.)
- opportunities for qualitatively new fundamental physics

+ Experimental feasibility studies (Bielefeld, ...)
[Nuclear + high energy particle]

$\Rightarrow$ Highest priority for field is an

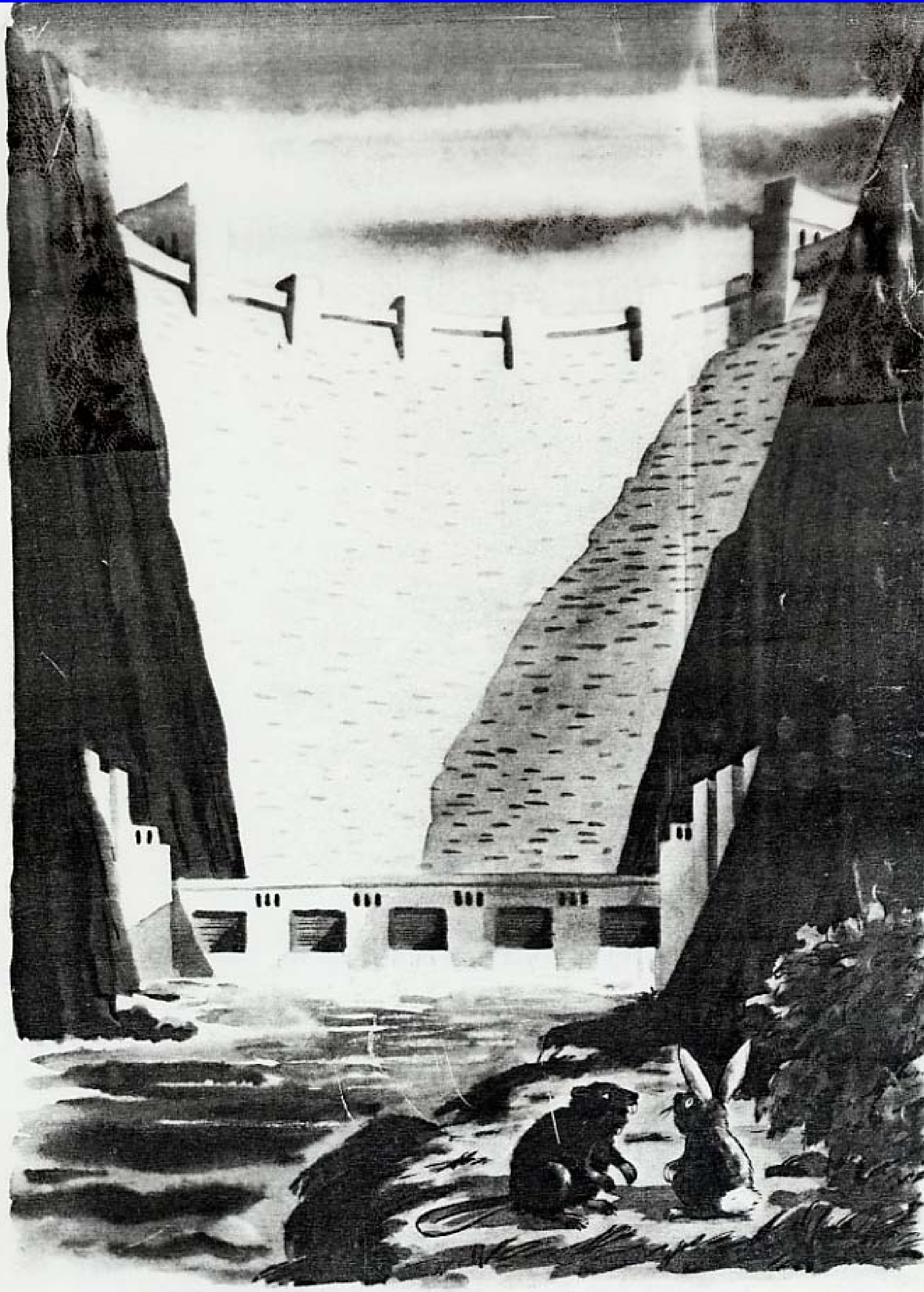
Ultra-relativistic heavy ion collider
$E/A \gtrsim 30$ GeV/A in c.of m.
A up to Uranium

$\Delta y \doteq 8$, equivalent to $E/A \sim 1.5$ TeV lab
Should include fixed-target physics at lower Δy ~
(equiv. to $E/A \sim 10$ GeV lab)

Shutting down of CBA in favor of “Desertron” (SSC) set the stage for building colliding beam heavy ion accelerator in the CBA tunnel!

Construction at 100 GeV/A driven by possibiity of producing jets that propagate through collision volume -- a wise decision.

Forlorn beam tunnel of the CBA (Isabelle), 1983



"I didn't actually build it, but it was based on my idea."

John Schiffer to Jim Leiss (DOE) & Marcel Bardon (NSF) Aug. 5, 1983

"Our increasing understanding of the underlying structure of nuclei and of the strong interaction between hadrons has developed into a new scientific opportunity of fundamental importance – the chance to find and to explore an entirely new phase of nuclear matter. In the interaction of very energetic colliding beams of heavy atomic nuclei, extreme conditions of energy density will occur, conditions which hitherto have prevailed only in the very early instants of the creation of the universe. We expect many qualitatively new phenomena under these conditions; for example a spectacular transition to a new phase of matter, a quark-gluon plasma, may occur. Observation and study of this new form of matter would clearly have a major impact, not only on nuclear physics, but also on astrophysics, high-energy physics, the broader community of science and on the world at large. The facility necessary to achieve this scientific breakthrough is now technically feasible and within our grasp; it is an accelerator that can provide colliding beams of very heavy nuclei and with energies of about 30 GeV per nucleon. Its cost can be estimated at this time only very roughly as about 150-200 million dollars. *It is the opinion of this Committee that such a facility should be built by the United States expeditiously, and we see it as the highest priority new scientific opportunity within the purview of our science."*

Main issue for RHIC was to discover the properties of nuclear matter under extreme conditions -- high temperatures, high densities:

-- entropy and equation of state

-- the nature of its excitations: quasiparticles, collective modes

-- transport of conserved quantities: energy-momentum, baryons, etc.

-- dynamics

-- stopping of hadronic and quark projectiles; energy dissipation

-- particle emission

Possible discovery of new states of matter

-- quark-gluon plasma: A GOAL, NOT *THE* SCIENTIFIC GOAL!

-- insights into π condensation, liquid-gas phase transition at low ρ, T?

Study behavior of QCD at large distance scales:

-- long range forces

-- deconfinement transition, order? sharp? Measure Λ_{QCD}

-- chiral symmetry restoration

-- plasma modes

-- confinement in multi-baryon systems

System would be strongly interacting!

Unusual objects:

-- multiquark states

--hadrons with heavy quarks

--extended droplets of large strangeness

--multi-baryon states of unusual chiral topology

--π-μ and other exotic atoms

--production of free quarks

Scientific questions in the 1983 NSAC Long Range Plan:

“What is the nature of nuclear matter at energy densities comparable to those of the early universe?”

“What are the new phenomena and physics associated with the simultaneous collision of hundreds of nucleons at relativistic energies?”

The most outstanding opportunity opened by an ultrarelativistic heavy ion collider is “the creation of extended regions of nuclear matter at energy densities beyond those ever created in the laboratory over volumes far exceeding those excited in elementary particle experiments and surpassed only in the early universe.”

Astrophysical motivations for studying dense matter

Neutron stars

$\rho > \rho_{nm}$, $T < 1\text{-}10$ MeV, $R \sim 10\text{-}12$ km, $M \sim 1.2\text{-}2\, M_\odot$

--birth, evolution and cooling (x-ray satellite observations, AXAF)

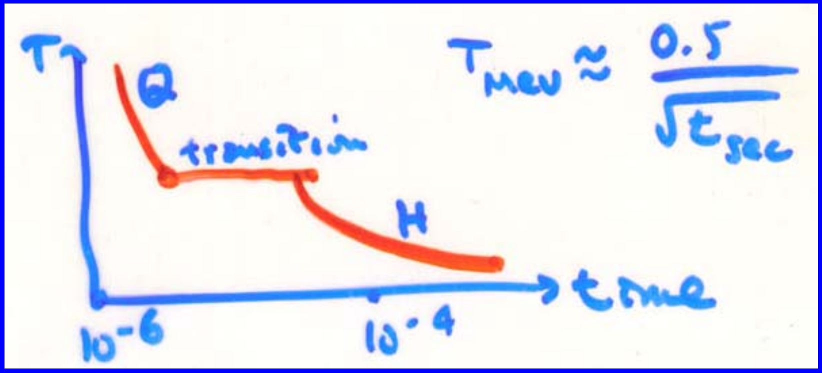
--upper mass limits, black hole identification

Supernova and gravitational collapse

-- bounce above ρ_{nm}, energy release

-- hot n-rich nuclei

Cosmology



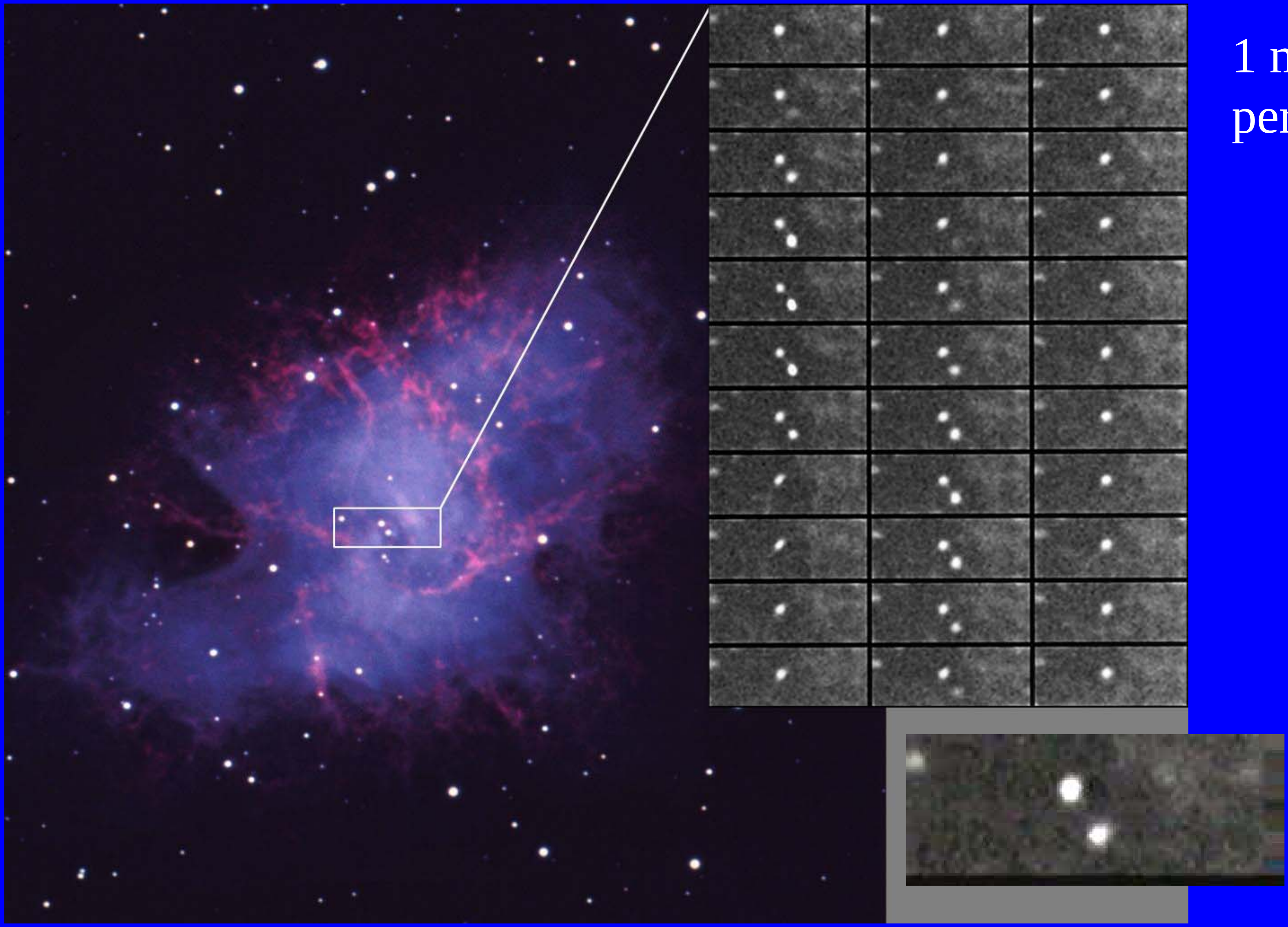
-- mini- black holes

$M \sim M_{jupiter} \sim 10^{-2} M_\odot$

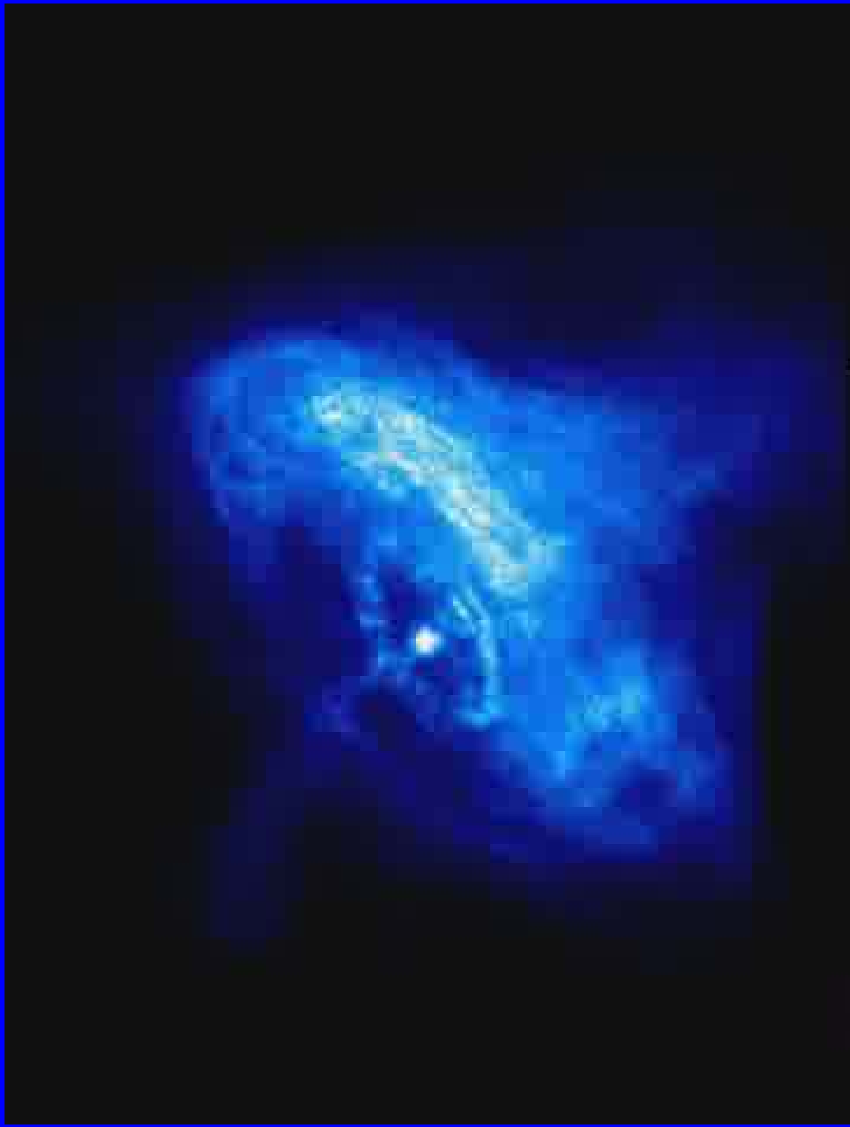
Cosmic rays

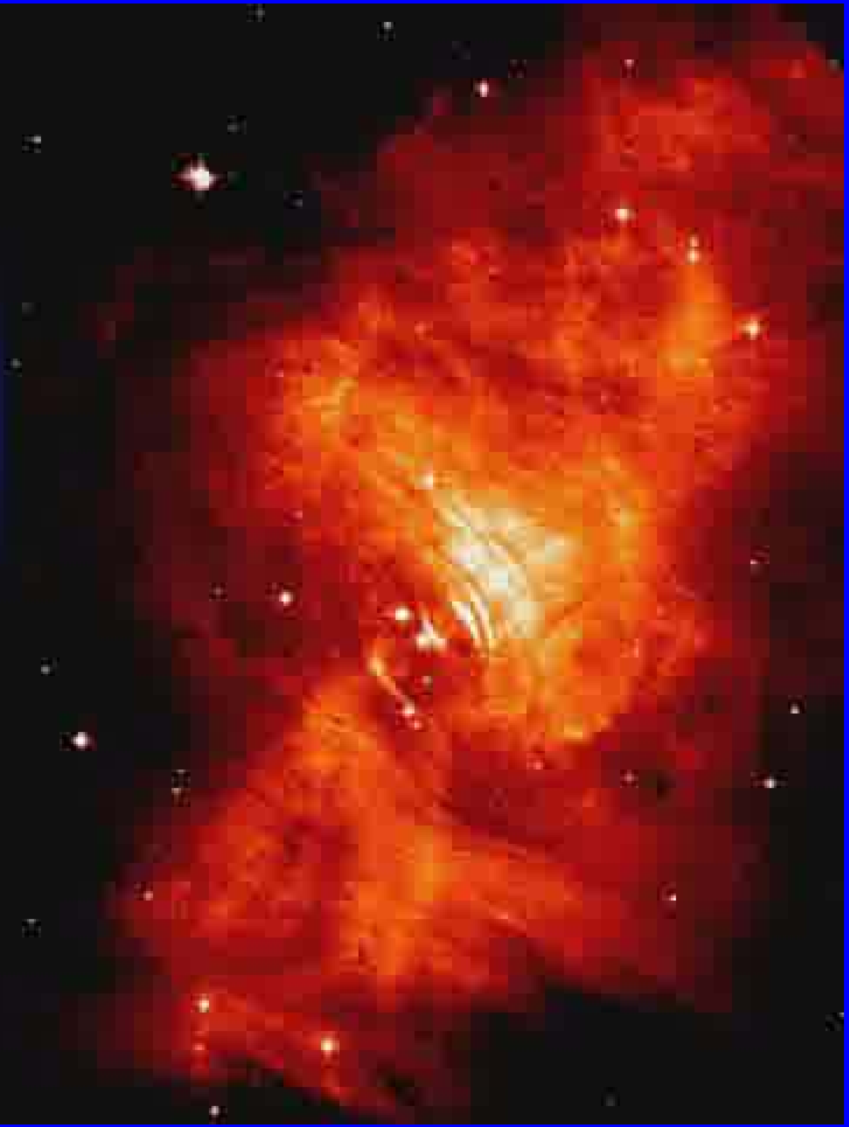
Crab Pulsar (period = 33 msec)

Supernova July 4, 1054 -- Pulsar discovery 1968



1 msec
per frame





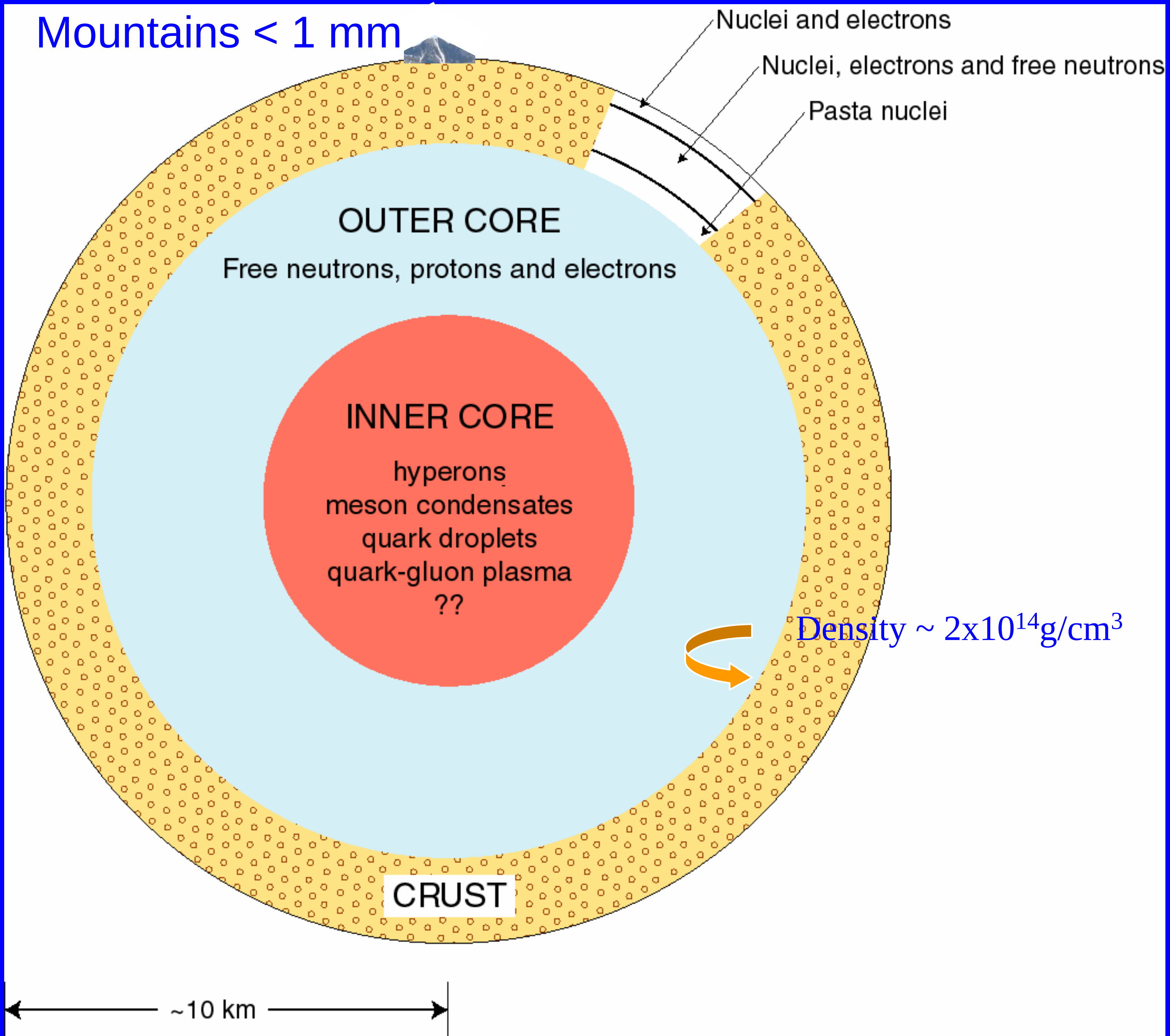
Chandra x-ray image

Hubble optical image

Cross section of a neutron star

Mass ~ 1.4 M_{sun}
Radius ~ 10-12 km
Temperature
~ 10^6-10^9 K

Surface gravity
~10^{14} that of Earth
Surface binding
~ 1/10 mc^2



Maximum neutron star mass -- and black holes

Equation of state of matter at high baryon density determines maximum possible neutron star mass, and thus the cut on black holes. Conventional cut on black hole candidates: $M_{max} = 3.2 M_\odot$. Improved knowledge of eq. of state leads to lower cut:

Knowing equation of state to

$\rho = 2\rho_{nm} \Rightarrow M_{ns} < 2.9\ M_\odot$

and to $4\rho_{nm} \Rightarrow M_{ns} < 2.2\text{-}2.3\ M_\odot$.

⇨ *many new small mass black hole candidates*

Mass function: $f_{opt} = (M_x^3 \sin i) / (M_x + M_{optical})^2 < M_x$

in low mass x-ray binaries

ex. Nova muscae, $f_{opt} = 3.1 \pm 0.4$

GRO J1655-40, $f_{opt} = 3.16 \pm 0.15$

PHYSICS $\boxed{50 \times 50}$ PROBLEM SET # 2

FALL 1983 DUE: JULY 17, 1984

1. Better lattice gauge calculations of transition region. Finite n_b too.

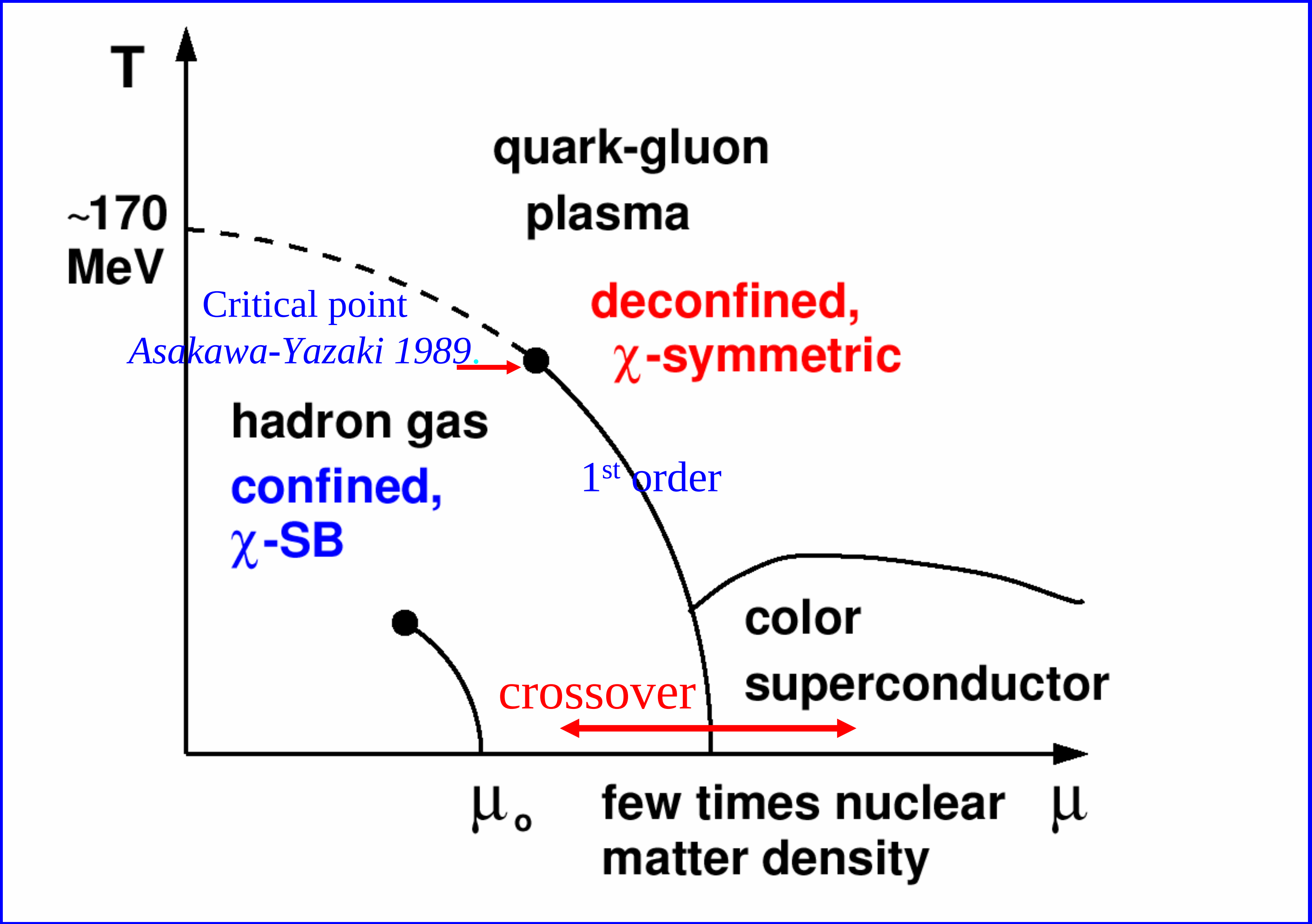
2. Better understanding of signals for plasma.

3. Nature and role of fluctuations.

4. Nucleon stopping power; width of frag. regions.

5. How to probe qcd plasma after it is discovered.

Phase diagram of equilibrated quark gluon plasma

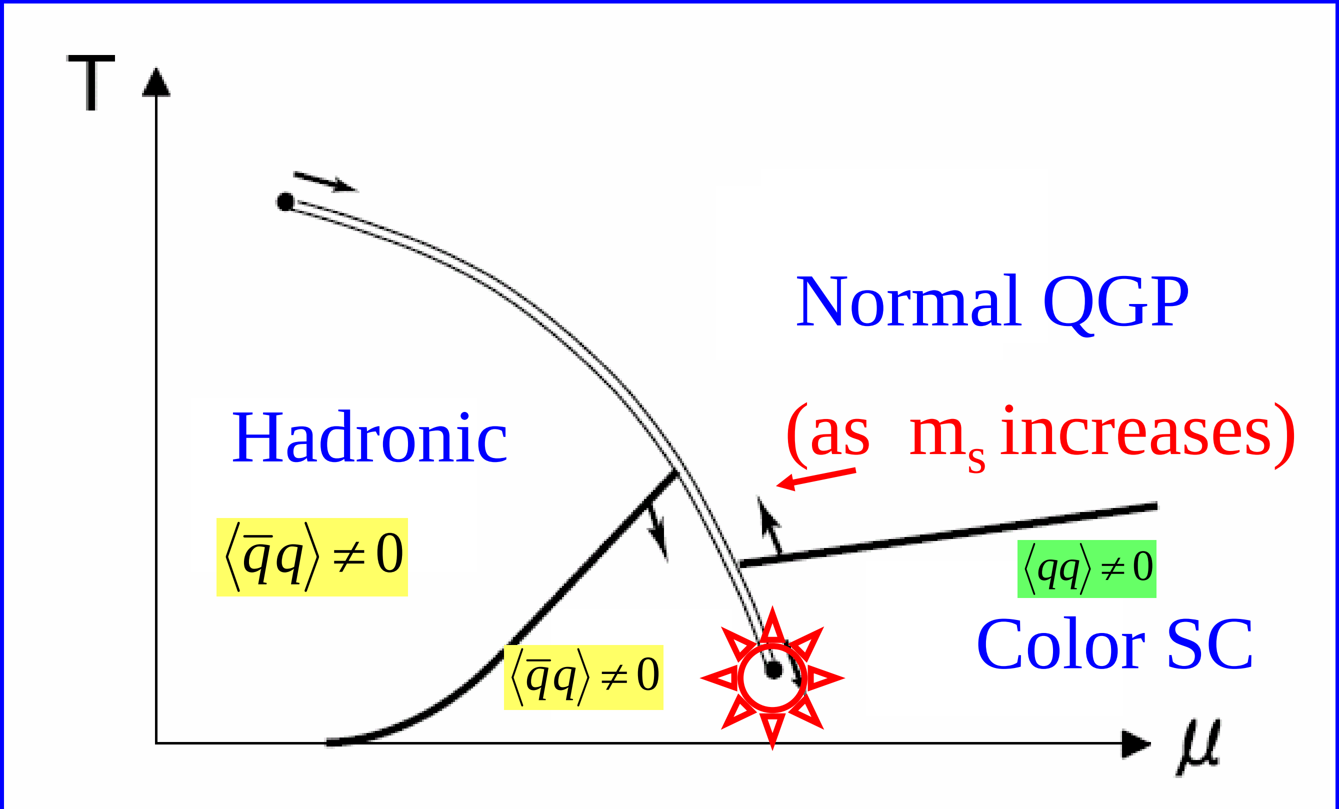


Karsch & Laermann, 2003

New critical point in phase diagram:

induced by chiral condensate – diquark pairing coupling via axial anomaly

Hatsuda, Tachibana, Yamamoto & GB, PRL 97, 122001 (2006)
Yamamoto, Hatsuda, Tachibana & GB, PRD76, 074001 (2007)



Too cold to be accessible experimentally at RHIC. Possibly at FAIR.

Order parameters

a,b,c = color
i,j,k = flavor
C: charge conjugation

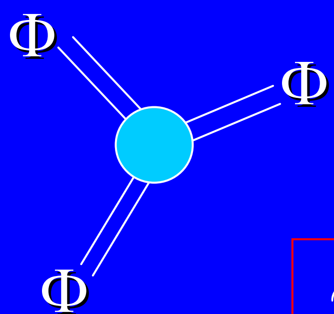
In hadronic (NG) phase: $\Phi_{ij} \sim -\langle \bar{q}_R^j q_L^i \rangle$

= color singlet chiral field

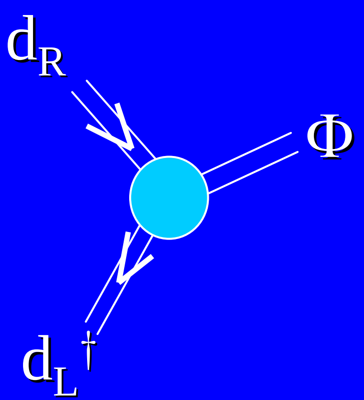
In color superconducting phase : $\langle (q_L)_b^j C (q_L)_c^k \rangle \sim \epsilon_{abc}\epsilon_{ijk}[d_L^\dagger]_{ai}$

$U(1)_A$ axial anomaly => Coupling via ‘t Hooft **6-quark** interaction

$$\sim \det_{i,j}\left(\bar{q}_R^j q_L^i\right)$$



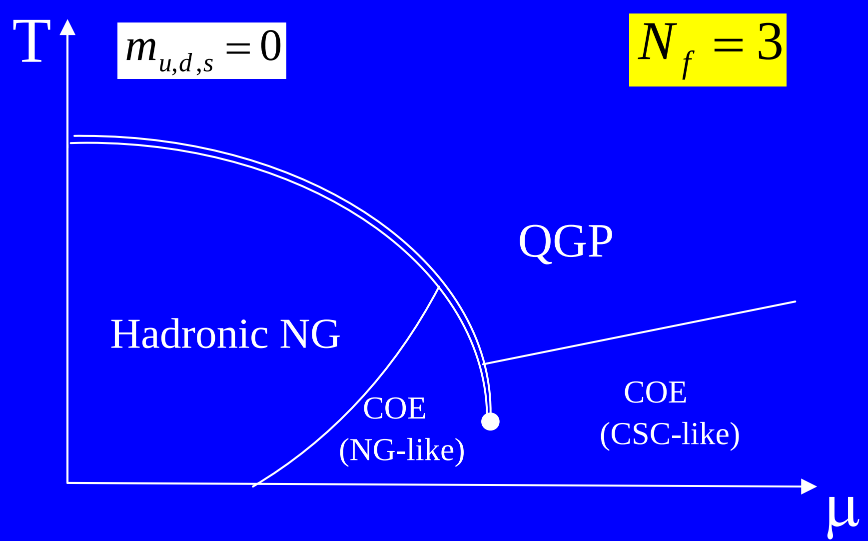
$\sim \Phi^3$

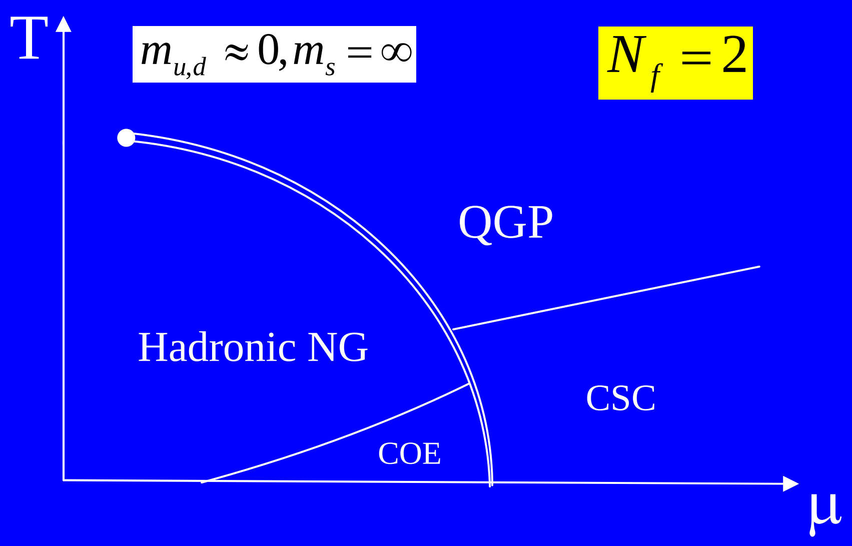


$\sim d_L{}^\dagger d_R \Phi$

Phase structure in T vs. μ

Deduce existence of critical point from Ginzburg-Landau expansion of free energy in chiral and pairing order parameters. To construct phase diagram in the (T, μ) plane requires dynamical picture to calculate G-L parameters.

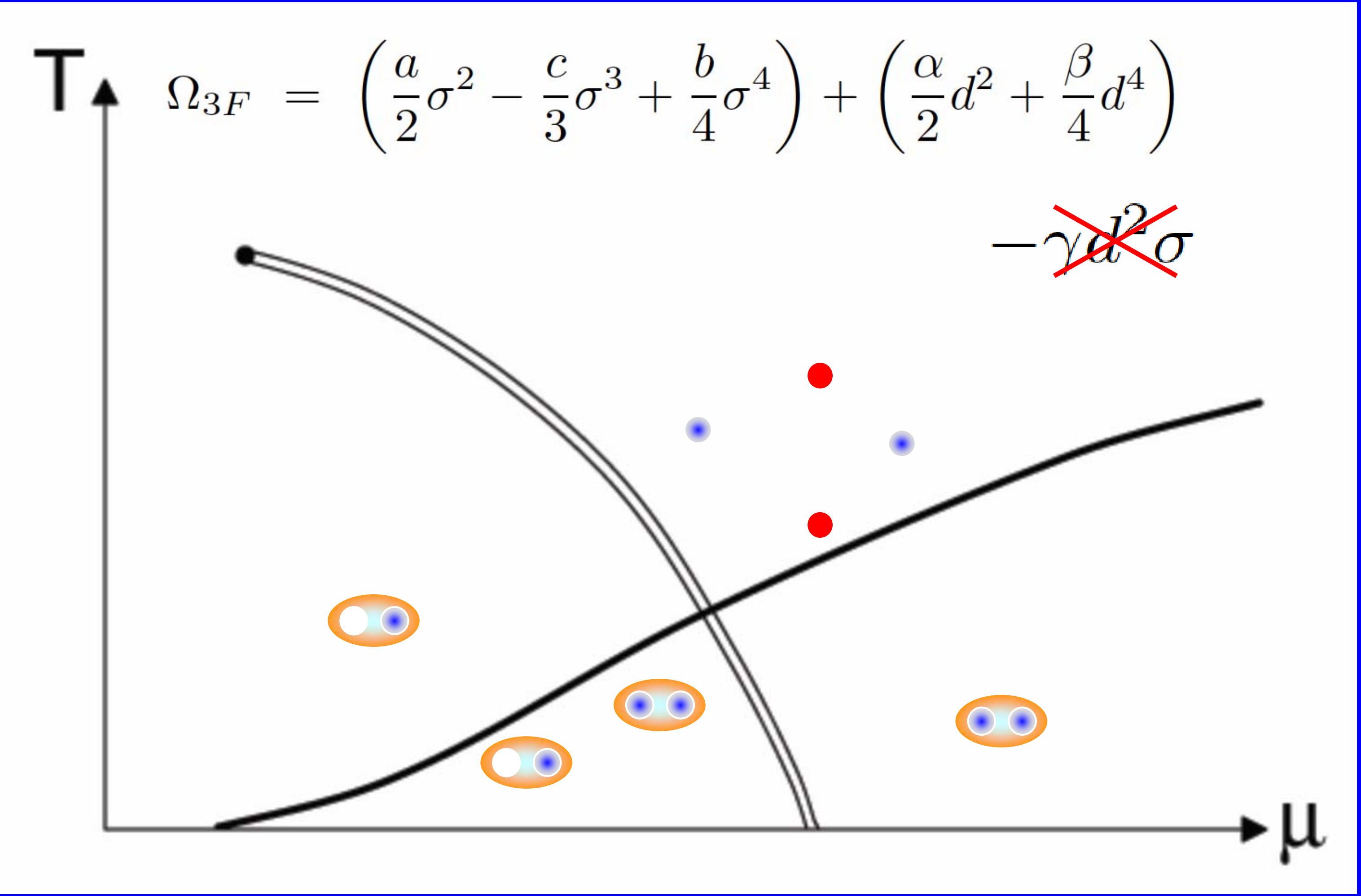




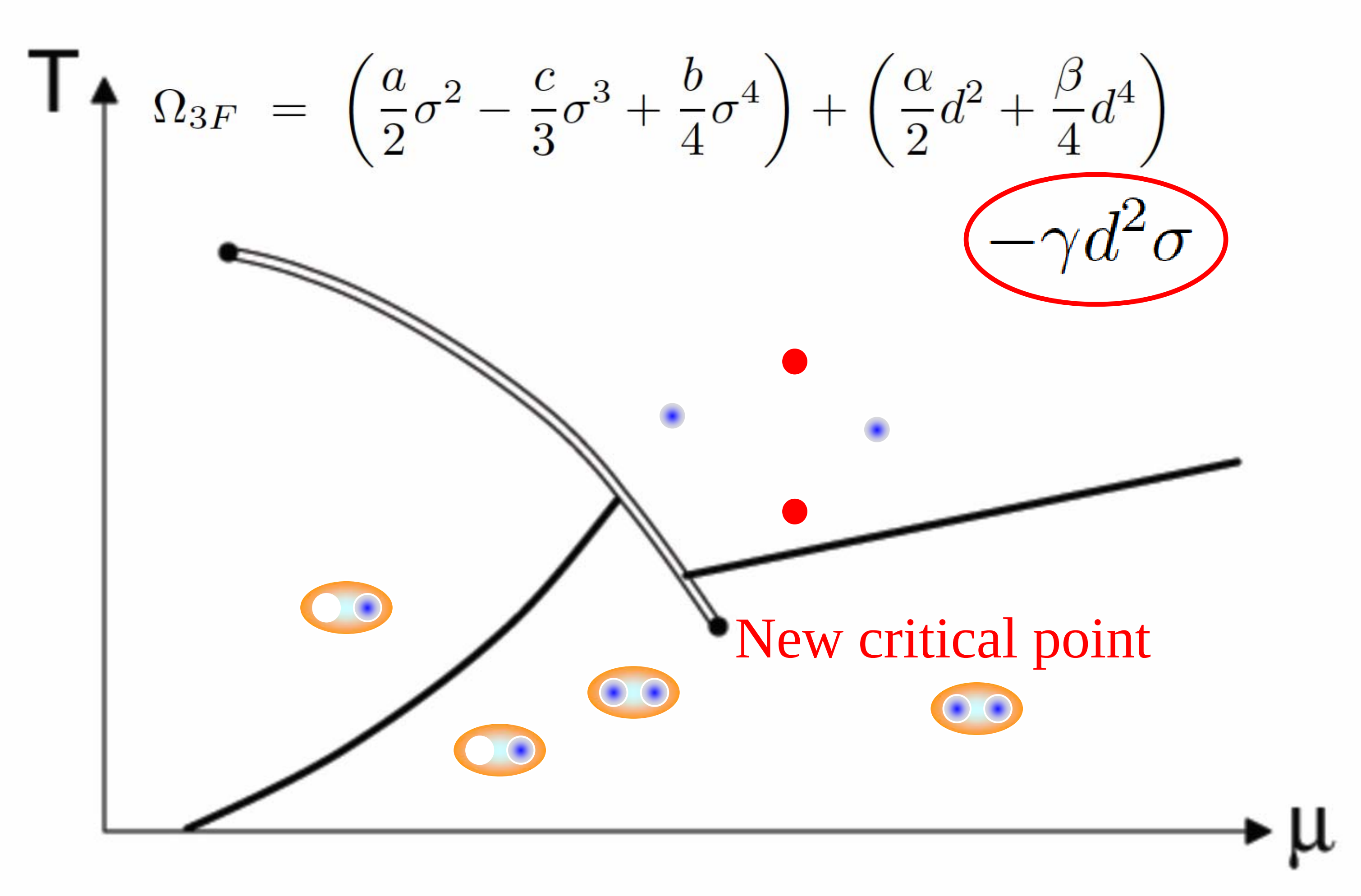
"Hadron"-quark continuity at low T (*Schäfer-Wilczek 1999*)

No anomaly-induced critical point for N_f=2 in $SU(3)_C$ or $SU(2)_C$

Schematic phase structure of dense QCD with two light *u,d* quarks and a medium heavy *s* quark without anomaly

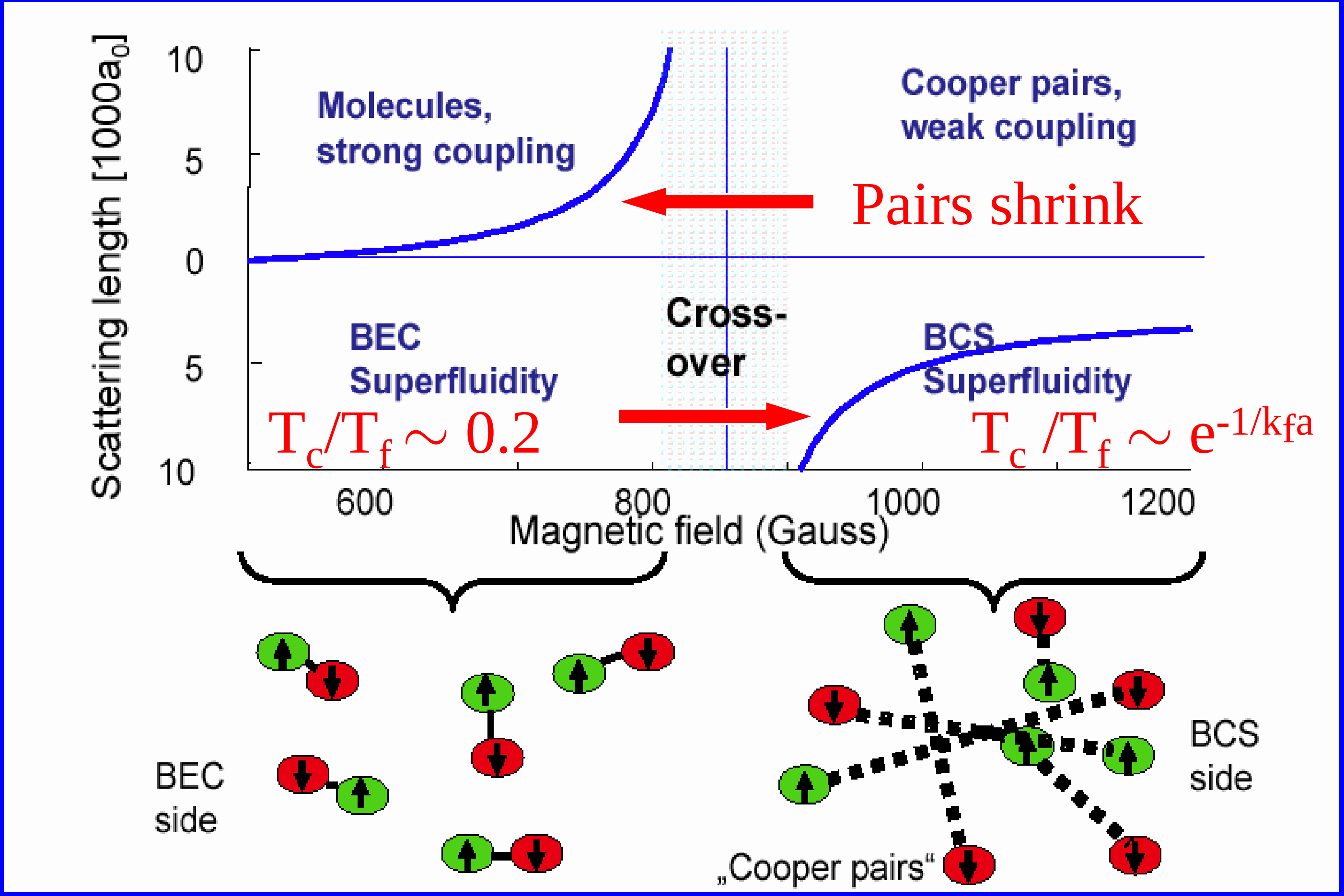


Schematic phase structure of dense QCD with two light *u,d* quarks and a medium heavy *s* quark with anomaly



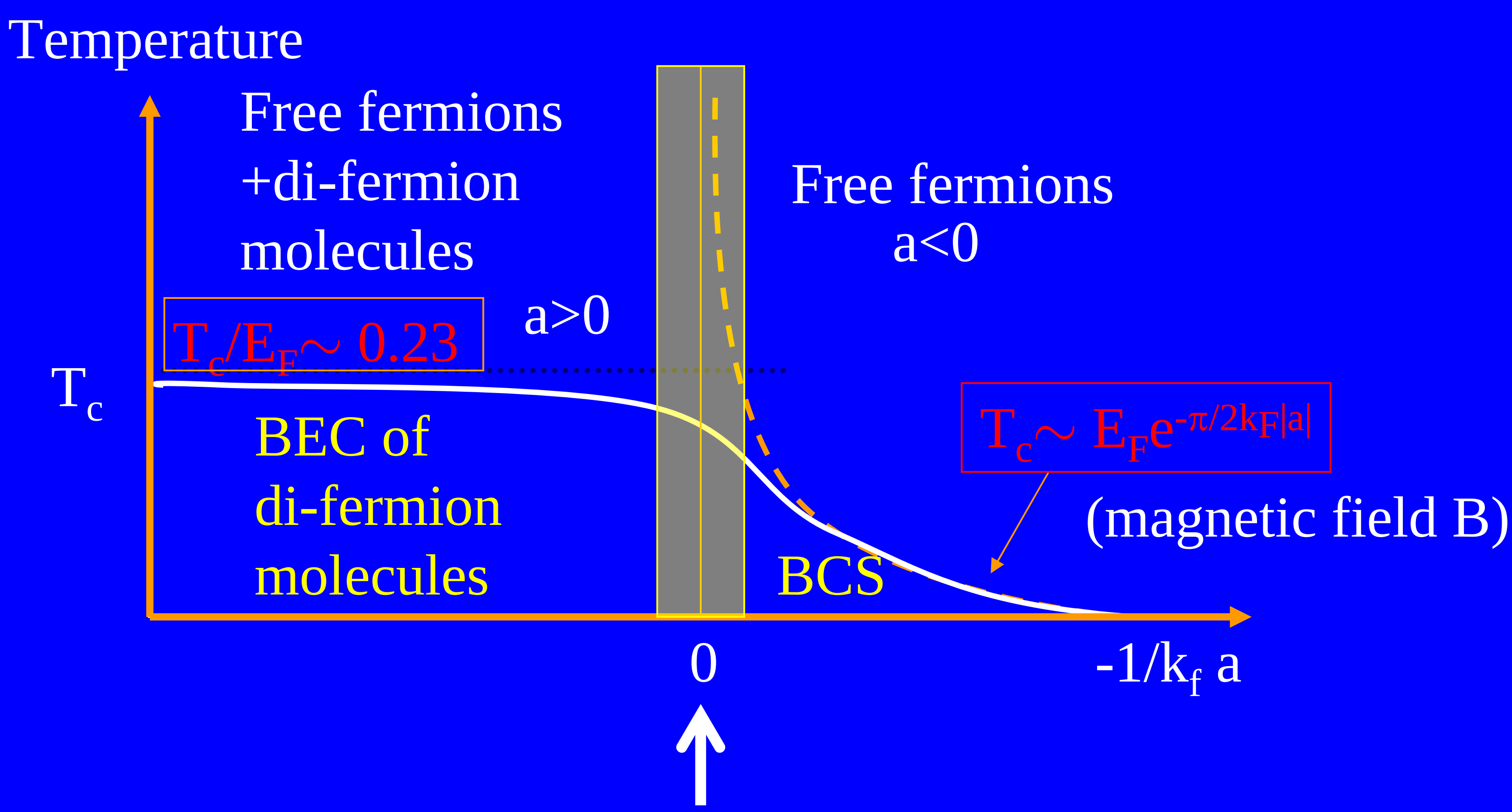
Hadron-quark matter deconfinement transition vs. BEC-BCS crossover in cold atomic fermion systems

In trapped atoms continuously transform from molecules to Cooper pairs: *D.M. Eagles (1969) ; A.J. Leggett, J. Phys. (Paris) C7, 19 (1980); P. Nozières and S. Schmitt-Rink, J. Low Temp Phys. 59, 195 (1985)*



^6Li

Phase diagram of cold fermions vs. interaction strength



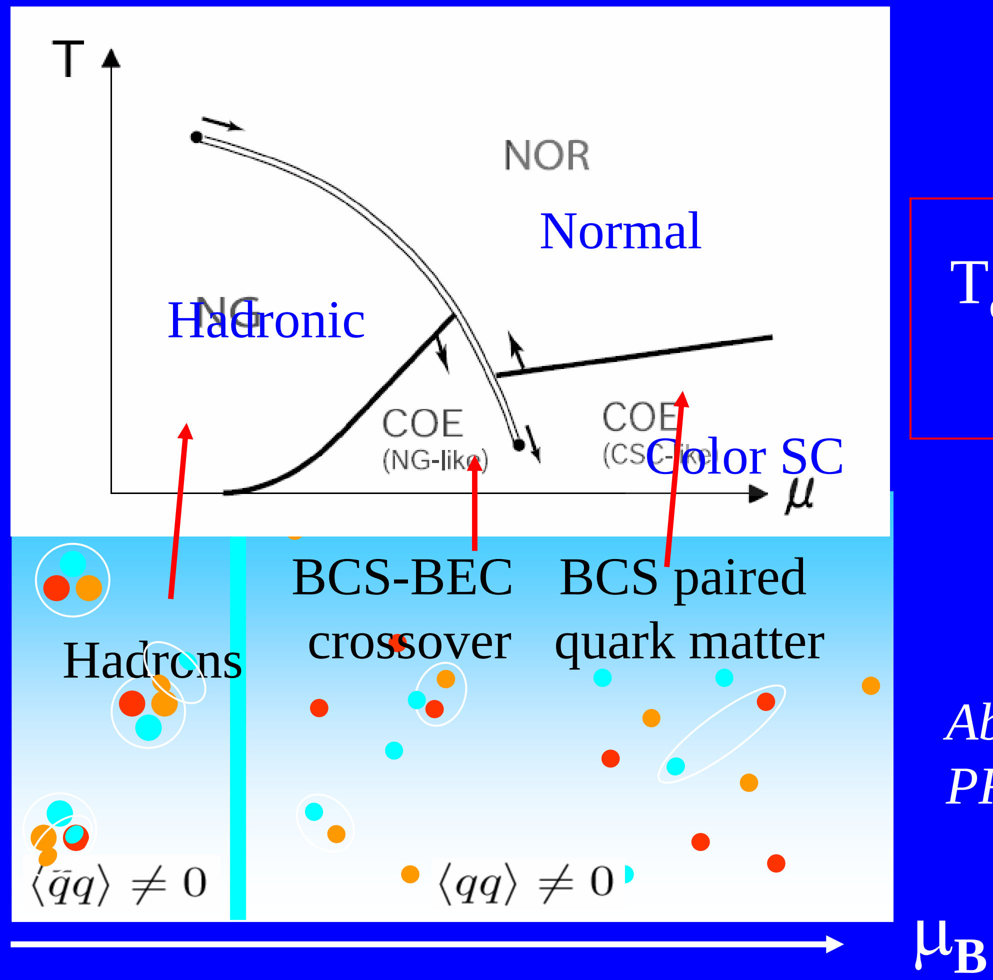
Unitary regime (Feshbach resonance) -- crossover

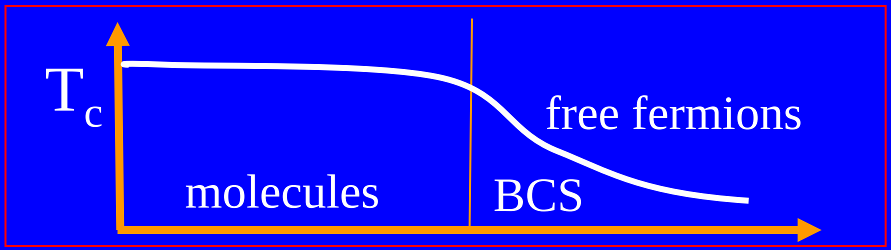
No phase transition through crossover

Deconfinement transition vs. BEC-BCS crossover

In $SU(2)_C$: Hadrons <=> 2 fermion molecules.
Paired deconfined phase <=> BCS paired fermions

In $SU(3)_C$

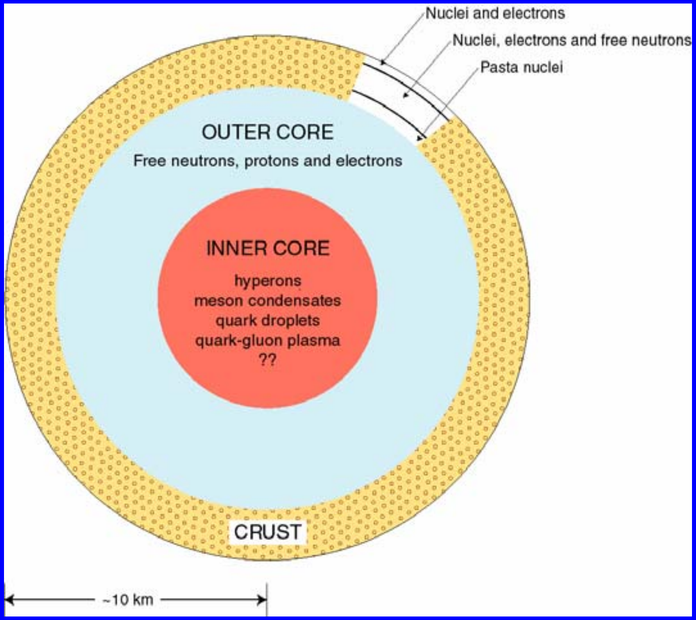




Abuki, Itakura & Hatsuda, PRD65, 2002

Quark matter cores in neutron stars

Canonical picture: compare calculations of eqs. of state of hadronic matter and quark matter. Crossing of thermodynamic potentials => first order phase transition.



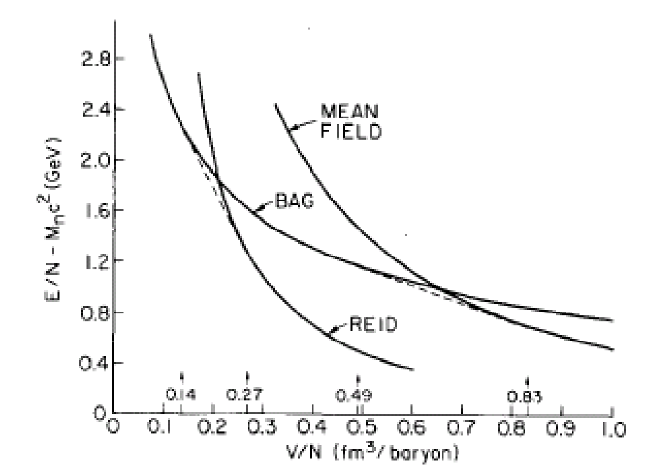


Fig. 1. Energy per baryon as a function of specific volume for the quark phase of neutron matter ("Bag") and two bracketing calculations of neutron matter ("Mean Field" and "Reid").

ex. nuclear matter using Walecka model, vs. bag model. *GB+S. Chin 1976*

Typically conclude transition at $\rho \sim 10\rho_{nm}$ -- not reached in neutron stars if high mass neutron stars ($M>1.8M_\odot$) are observed (e.g., Vela X-1, Cyg X-2) => no quark matter cores

Limitations of equation of state based on nucleon-nucleon interactions

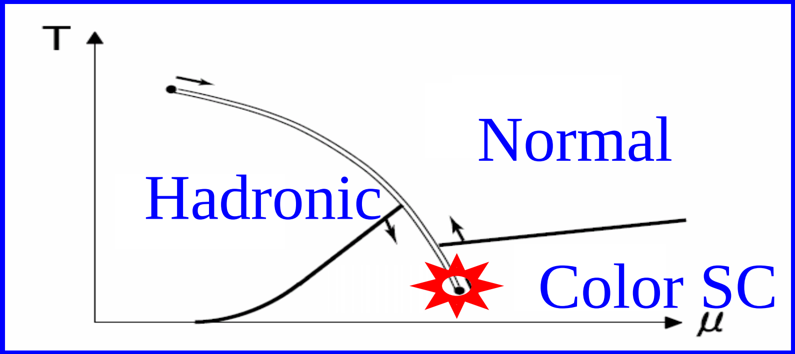
Accurate for neutron star matter in neighborhood of n_{nm}.

Beyond few n_{nm} :
cannot describe forces in terms of static few-body potentials.
Characteristic range of nuclear forces $\sim 1/2m_\pi$ =>
importance of 3 and higher body forces $\sim n/(2m_\pi)^3 \sim 0.4n/\{fm\}^{-3}$.
For $n >> n_{nm}$, no well defined expansion.

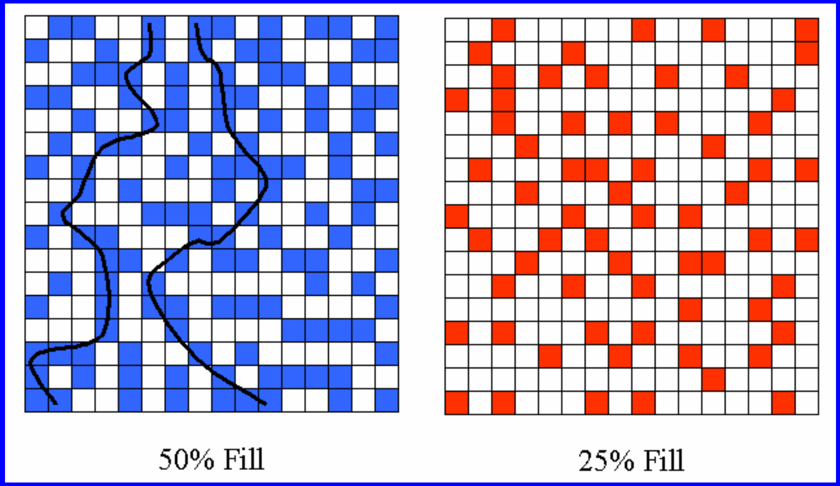
Further hadronic degrees of freedom enter

Cannot describe high density matter in terms of well-defined "asymptotic" laboratory particles.

More realistically, expect gradual onset of quark degrees of freedom in dense matter



New critical point suggests transition to quark matter is a crossover at low T



Consistent with percolation picture, that as nucleons begin to overlap, quarks percolate [*GB, Physica (1979)*] :

$$n_{perc} \sim 0.34\ (3/4\pi\ r_n^{\ 3})\ \ \mathrm{fm}^{-3}$$

Quarks can still be bound even if deconfined.

Physics goals of RHIC

- Achieve highest energy densities in extended matter for relatively long times
- Learn the dynamics of high density matter: energy deposition, stopping, formation of excitations, onset of equilibration, hadronization, freezeout
- Search for collective effects beyond individual pp scattering, or pA scattering
- Study role of new degrees of freedom
- Produce and study quark-gluon plasma with large A at E above a few GeV/fm^3
- Extract nuclear equation of state, application to astrophysics

1995 Long range plan meeting

What are the properties of matter at extremely high energy, or baryon, density? From nuclear matter scales (ρ_0=0.16/fm^3, E_0=0.15GeV/fm^3) to orders of magnitude beyond?

- What are its effective degrees of freedom? From nucleonic to hadronic to quark-gluon.
- What are the states of matter? Recognizable quark-gluon plasma? Strangelets? ...?
- What is the structure of qcd on large distance scales? Phase transitions? Monopoles?
- Surprises!

(thanks to Bill Zajc)

Have our original goals been reached?

Discovery of quark gluon plasma:

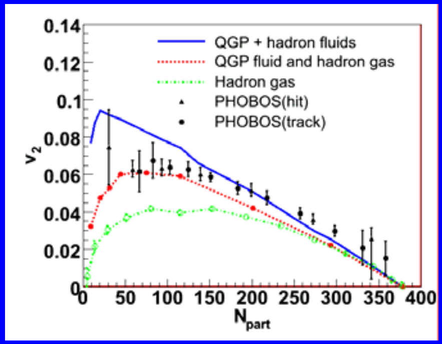
High energy densities -- and new state of matter -- achieved.

Plasma very strongly interacting; behaves collectively.

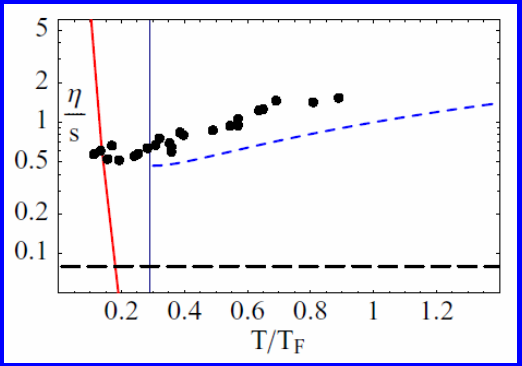
Transport properties: Very small viscosity; consistent with AdS/CFT bound on η/s.

Connections with ultracold trapped fermionic atomic systems near Feshbach resonance. Also very low η/s.

Impact on cosmology! QGP in early universe highly correlated system.

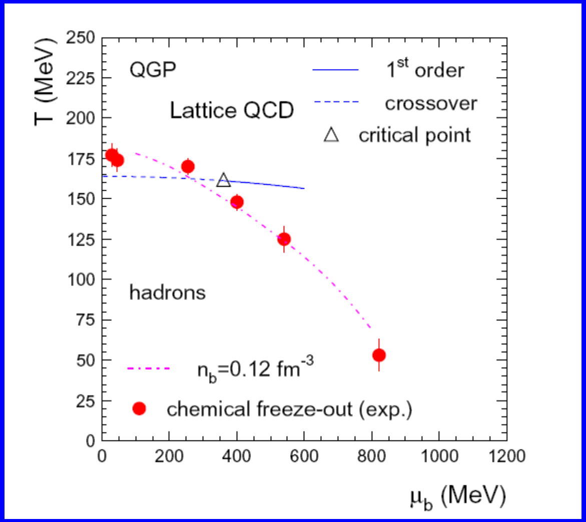


Hirano



Rupak & Schaefer

Phase transitions: problems of lattice gauge theory at finite baryon density make detailed comparison of firm theoretical predictions with experiment much more difficult. Learning Λ_{qcd} and properties of qcd on large scales from heavy ions still in the future.



Braun-Munzinger & Stachel

Neutron stars: to learn equation of state need to extrapolate from high temperature to sub-MeV degenerate regime. Understanding onset of quark degrees of freedom with increasing ρ still in the future.